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Date: February 10, 2000  
Box PATENT APPLICATION  
Assistant Commissioner for Patents  
Washington, D. C. 20231

Sir:

RE: Application of: Di Cao and Kenzo Hara  
For: METHOD OF DESIGNING GEOPHYSICAL SURVEYS  
Docket No.: 26.0178

JC564 U.S. PTO  
09/501445  
02/10/00

Enclosed are the following:

- ☒ Application including specification, claims and 2 sheets of drawings;
- ☒ Declaration;
- ☐ Priority Document;
- ☐ Information Disclosure Statement and PTO-1449
- ☐ Assignment to: SCHLUMBERGER TECHNOLOGY CORPORATION  
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FOR	NUMBER FILED	NUMBER EXTRA	RATE	BASIC FEE \$690
TOTAL CLAIMS	13 - 20	0	x \$18	0
INDEPENDENT CLAIMS	1 - 3	0	x \$78	0
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Three copies of this letter are enclosed.

Respectfully submitted,

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## METHOD OF DESIGNING GEOPHYSICAL SURVEYS

## FIELD OF THE INVENTION

The present invention relates to methods for designing geophysical surveys such as seismic surveys. In particular, the methods involve determining the positions of sources and receivers for conducting the survey, especially in borehole seismic surveys such as vertical seismic profiles.

## BACKGROUND OF THE INVENTION

The general arrangement of a vertical seismic profile (VSP) survey is shown in Figure 1. A tool 10, typically comprising an array of seismic receivers (e.g. geophones) 12, is positioned in a borehole 14 by means of a logging cable 16 connected to surface equipment 18. One or more seismic sources 20 (e.g. airguns) are positioned at the surface some distance from the borehole 14. When the source(s) is fired, seismic waves S travel through the formations 22 surrounding the borehole 14 and are reflected in part from changes in acoustic impedance in the formations due to the presence of bed boundaries 24, and are detected by the receivers 12 in the borehole 14. The signals recorded from the receivers 12 can be interpreted by use of a suitable geophysical model to characterise the formations 22, especially the shape and location of the boundary 24. Often the VSP survey is designed with the intention of investigating a particular area or target within a roughly known boundary. Variations of such surveys can include reverse VSP (sources in borehole, receivers at the surface), walkaway VSP (measurements made from a series of source firing as it is moved progressively further from the borehole), 3D VSP (use of a 2D array of sources at the surface), and drill bit seismic (drill bit as source of signals, receivers at the surface). Tools and techniques for use in VSP surveys are generally well known in the oil and gas industry.

In designing a seismic survey, attention must be paid to the particular regime in which the survey is to be conducted. For a typical surface seismic survey (both sources and receivers located at the surface), reflection wave propagation is essentially symmetric from the source to reflecting boundary and back to the receiver. The symmetry is modified by aspects such as the structure of the underground formations but this can be taken into account by using a model

which can anticipate such changes. Also, P - S conversion in the waves can result in asymmetry. Borehole seismic surveys such as VSPs are by their very nature asymmetric. Therefore, the problem of designing them is more complex. Since the object of a VSP is often to characterise a region of a boundary (a "target"), especially if the object is to image this target, the positioning of the tool in the borehole and the positioning of the source(s) at the surface is important if the appropriate reflected signals are to be recorded in the borehole. However, it is often the case that it is not possible to have a completely free hand when it comes to positioning the source and receivers. For example, surface geographical features (rivers, lakes, cliffs, gullies, etc.) can limit the ability to place the sources. Also, aspects of the borehole (direction, casing, production and completion equipment) can limit the ability to position the tool in the borehole. Finally, financial and time considerations can also apply limiting the number of sources available or the ability to make measurements with the tool at a number of locations in the borehole.

A typical job design process involves identifying the possible positions for the particular number of sources and receivers available for that job, and using a geophysical model of the underground formations to trace ray paths from the source(s) to the receivers. The positions of the sources and receivers are then adjusted until the model shows that the detected signals arrive from the target. The adjustment of the positions is performed by the user who uses experience and available information to estimate the effect of changing the positions before testing using the model. This makes the whole design process highly dependent on the skill and experience of the user.

It is an object of the present invention to provide a method suitable for designing geophysical surveys and in particular for identifying suitable positions for sources and receivers.

## SUMMARY OF THE INVENTION

The present invention provides methods of designing geophysical surveys, comprising:

defining a target of interest;

defining a receiver location region in a predetermined position relative to the target;

defining positions within the receiver location region for a predetermined number of receivers;

preparing a geophysical model which includes the target, the receiver location region and a source location region;

5 using the model to propagate ray traces from the receiver positions to the source location region via the target;

sub-dividing the source location region according to ray trace density resulting from the propagation; and

10 designating one or more potential source positions according to the ray trace density in a respective sub-division.

The geophysical survey can be a seismic survey, preferably a borehole seismic survey. Such a survey can include receiver locations in a borehole and source locations at the surface. In such surveys, the number and position of receivers is often less variable than the number and/or position of sources. Consequently, the approach of propagating ray traces from the receivers to the surface via the target allows an appropriate source location to be defined. In certain circumstances it is also possible to use the same approach with a predetermined number of sources in a source location, and to propagate ray traces to define receiver locations.

20 The method provided by the invention is applicable to surface seismic, VSP, 3D VSP, reverse VSP, drill bit seismic and other such surveys.

The target will typically comprise a region in a horizon in the formations around a borehole. One particular example is an area surrounding a reef in a horizon. The target can typically be designated on the basis of an earlier seismic survey, such as a surface survey.

The receiver location is typically within a borehole and may comprise a portion of the borehole in which it is considered possible to position one or more receivers. More than one location is also possible. The receiver positions can be determined using knowledge of the receiver separations of a tool to be used or can be equidistant spacings in the receiver location give the

number of receivers to be used. For example, for a given interval of borehole, if a known number of receivers will be used, the first set of positions can be equally spaced along that interval.

The geophysical model can be of a type generally used in designing seismic surveys. The model needs sufficient detail to identify the target but does not need to be of exceptional accuracy or resolution, for example a macro-model will be appropriate. A suitable model will include the reflecting horizons and the assumed acoustic impedances of the layers of formation in the model. The model includes in it the receiver location and positions, typically located in the position of a borehole included in the model. The surface will also be defined to allow source location regions to be defined.

Ray traces can be propagated using the model from each receiver position to the surface in the source location region. This based on the theory of reciprocity of ray paths between sources and receivers. In cases where the source positions can be specified more accurately than the receiver positions, ray tracing can be from source to receivers. The result of this ray tracing will be a ray trace density distribution in the source location region. By sub-dividing this region according to ray trace density, it is possible to identify those positions with a high ray trace density which will correspond to optimum positions for sources in that region. Because of the reciprocity, a position in the source region with high ray trace density will result in a high signal level in the receiver location region previously defined. A visual display can show the source positions by use of colour, shading or any other visual symbol.

A particularly preferred embodiment of the invention is implemented on a computer with the receiver location region and position, target and source location region being defined on a display, and the ray paths and source positions being determined by operation of a suitable program.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a prior art VSP configuration;

Figure 2 shows a flow diagram of a method according to the invention;

Figure 3 shows a flow diagram of the steps in building a geophysical model; and

Figure 4 shows a schematic view of a geophysical model with the borehole, receivers, target and ray tracing displayed thereon.

## 5 DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention will now be described by way of example, with reference to the accompanying drawings. In the particular case described, the invention is implemented in a software environment such as GeoFrame available from Schlumberger GeoQuest but it will be appreciated that the methodology described can be applied to other such environments while still  
 10 retaining the essential features of the invention and so is not limited to implementation in this environment. Unless otherwise specified, functional elements referenced in this description can be found in GeoFrame.

The embodiment of the invention described here is the design of a VSP survey for the purpose of  
 15 imaging a reef in the formations surrounding the well in question. The basic steps are shown in Figure 2 and in this case comprise:

- building a geophysical model;
- defining receiver locations in the well within the model;
- defining the target (e.g. reef);
- 20 - ray tracing from receivers to surface via target;
- defining source locations on surface; and
- validate by ray tracing from source locations to receiver locations via target.

### Building the Geophysical Model

25 The invention requires the use of a geophysical model, that is to say a representation of the three dimensional properties of the underground formations in the region being investigated. Such a model can be formulated using the Common Model Builder of GeoFrame and inputting suitable geophysical data, such as surface seismic data that has been interpreted using appropriate known methodologies. The general approach in the preferred embodiment is to generate a model by  
 30 defining the volume of interest; assigning surfaces to the volume of interest, the surfaces defining the boundaries between layers of different properties; and defining the properties of the layers (see flow chart of Figure 3).

### Defining Volume of Interest (VOI)

The VOI is defined relative to a datum point in terms of extent in Cartesian co-ordinates X, Y and Z. The upper Z limit being the surface. The VOI is therefore a 3D matrix in which the operations of the invention will be conducted. The VOI must include the target of interest (e.g. the reef), seismic receiver locations (e.g. the well), and source locations (e.g. ground surface or sea bed).

### Import Surfaces

GeoFrame can have a number of 2D grid files representing surfaces stored. The 2D grid files are essentially 2D matrices in the XY plane of data points relating to the Z dimension of the surface at that point. Importing the 2D grid files to the volume of interest creates a series of surfaces extending across the XY co-ordinates and varying in the Z co-ordinate. Typically, one or more of these surfaces will include features of the target of interest. For example, the lowest surface might include a feature such as a reef which it is desired to image with a VSP survey. Each surface will typically be assigned a name and, if computational power is limited, the data contained in the grid file may be compressed or decimated to some degree. The top of the model (typically ground level or sea bed) may be already present in the model or may be considered flat according to requirements.

### Assign Material Properties

Adjacent surfaces define volumes or layers of the formation which will have different material properties. The properties can be assigned and can be derived from well logs, offset data or other models. The material properties can include Vp/Vs ratio (ratio of compressional and shear velocities), Vp (compressional velocity) value and density of the formation. In a simple model, these values can be fixed, the layer describing a homogenous isotropic formation. More sophisticated models can allow for variation of these properties with distance from a datum point according to a predetermined gradient and/or within predefined limits for an inhomogenous and/or anisotropic formation. Since the purpose of this model is for designing a VSP survey, the properties assigned will be those that affect propagation of seismic waves through the formation.

This model can conveniently be displayed in visual form on a screen so as to be manipulated by a user within a suitable graphical user interface environment. Having built the geophysical model, the borehole, receiver location, target and source locations can be defined. Figure 4 shows a schematic view of a simple one layer model (two surfaces, ground level and target) for ease of understanding.

### Defining Receiver Locations

Once the model has been constructed, receiver locations can be defined. In the case of a VSP survey, the receivers 113 are located within a borehole 114. In order to image the target, seismic signals are generated at the surface, propagate down through the formations, are reflected back up from the target and received in the borehole. Consequently, it is necessary to select a portion 115 of the borehole 114 above the surface 124 with the target. Other matters which might affect the selection of the portion of the borehole in which the receivers 113 will be placed are size of the borehole, presence or absence of casing, hole condition, direction and inclination of borehole trajectory, etc. Having taken the appropriate factors into consideration, the receiver location can be defined in the model in terms of the X, Y and Z co-ordinates of the upper and lower limits of the receiver location 115 (borehole). Also, the number of receivers in the borehole is defined. In a simple form, receivers 113 can be considered equally spaced though the portion 115 of the borehole 114 defined. Alternatively, a number of receivers can be distributed within a more limited part of this location.

### Defining Target

The target, a reef 126, appears in one of the surfaces 124 of the model. This surface is selected and the portion of the surface (polygon) 126 containing the reef is defined in terms of X, Y and Z co-ordinates defining a sub-volume.

### Ray Tracing to Surface

The next step is to trace ray paths R' from the receivers 113 to the target 126 and determine where rays R'' will intersect the ground surface 130 when reflected by the target 126 and propagated through the layers of the model. Ray theory is used to trace the ray paths by means of algorithms coded into a suitable software package. No one particular implementation of such a software package is believed to be preferable over any other and a number of such packages are known to be available (general references for the techniques used can be found in a number of publications, for example *Chapman, C.H. and Drummond, R., 1982, Body-wave seismograms in inhomogeneous media using Maslov asymptotic theory, Bull. Seism. Soc. Amer., 72, S277-S317,* and *Coates, R.T. and Chapman, C.H., 1990, Ray perturbation theory and the Born approximation, Geophys. J. Int. 100, 379-392*). A suitable package will have the following features:

Dynamic ray tracing in inhomogeneous isotropic or anisotropic, tessellated 3D models (other alternatives are hybrid/irregular grid models);



Library developed on ray shooting methods where the ray (Hamilton) equations (ordinary differential equations) are solved;

Useful in models with general geometry and velocity functions;

Ray types (reflections, converted waves, transmissions and multiples) can be defined generally and precisely;

General heterogeneity of geophysical properties allowed;

General elastodynamic rays allowed;

Kinematic and dynamic ray results; and

Fast and efficient paraxial interpolation and extrapolation.

The preferred way to define ray traces is to define a ray tracing cone for each receiver 113. This is defined by the cone angle, the number of points around the circumference of each cone at which a ray is propagated and the number of concentric cones for each receiver. The azimuth and inclination of each receiver cone is set such that the ray traces intersect the target. For example, each receiver can have five concentric cones each separated by  $1^\circ$ , each cone propagating a ray every  $30^\circ$  of azimuth. Once the ray tracing cones are specified and directed at the target, the rays can be propagated from each receiver to the target and then (reflected) on to the surface, taking into account of the formation properties as defined in the model. Where the rays intersect the surface (upper limit) of the model, a ray density histogram 132 can be determined. This can include the simple geometric density (number of rays for a given surface area) or can include dynamic effects indicating the most energetic path to the surface (i.e. the effective energy flux at the surface for a given ray path). The histogram in this case indicates the regions of high energy at the surface being a combination of the number of ray paths and the energetic nature of these paths.

#### Define Source Locations

Using the ray density histogram 132, one or more source locations 120 can be defined. Because the ray propagation is reciprocal between sources and receivers, a high ray density at the surface when propagated from the receivers means that a source placed at that point and rays propagated through the same model to the target will result in a relatively high ray density at the borehole. Since surface features can limit the ability to position a source, it is not always possible to position the source at the highest density position. However, selecting one or more of the highest density locations should provide relatively high signal levels at the borehole.

#### Validate

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## WE CLAIM

- 1 A method of designing geophysical surveys, comprising:
  - i) defining a target of interest;
  - 5 ii) defining a receiver location region in a predetermined position relative to the target;
  - iii) defining positions within the receiver location region for a predetermined number of receivers;
  - iv) preparing a geophysical model which includes the target, the receiver location region and a source location region;
  - 10 v) using the model to propagate ray traces from the receiver positions to the source location region via the target;
  - vi) sub-dividing the source location region according to ray trace density resulting from the propagation; and
  - 15 vii) designating one or more potential source positions according to the ray trace density in a respective sub-division.
- 2 A method as claimed in claim 1, wherein the geophysical survey comprises a borehole seismic survey.
- 20 3 A method as claimed in claim 2, wherein the target comprises a region of a surface of a formation surrounding the borehole.
- 4 A method as claimed in claim 2, wherein the receiver location region comprises a portion of the borehole in which one or more receivers can be positioned.
- 25 5 A method as claimed in claim 1, wherein the geophysical model includes identification of layers of underground formations and material properties of these layers.
- 6 A method as claimed in claim 1, further comprising constructing a ray trace density histogram in the source location and using this histogram to define the source locations.
- 30 7 A method as claimed in claim 1, wherein the step of preparing a geophysical model comprises the steps of:

- a) defining a volume of interest;
- b) defining surfaces within the volume of interest to delimit layers of the model; and
- c) assigning material properties to the layers of the model.

5     8     A method as claimed in claim 7 wherein the surfaces are defined in terms of two dimensional arrays of data representing surface position at that point in a third dimension.

9     A method as claimed in claim 7, wherein the material properties include  $V_p/V_s$  ratio, compressional velocity, and density.

10     10     A method as claimed in claim 7 further comprising defining a borehole location within the volume of interest.

15     11     A method as claimed in claim 7, wherein one of the surfaces contains the target and including the step of defining a portion of the surface containing the target.

20     12     A method as claimed in claim 1, wherein the step of propagating ray traces from the receiver locations to the source locations comprises defining at least one ray tracing cone for each receiver location, and adjusting the direction and inclination of the cone to intersect the target

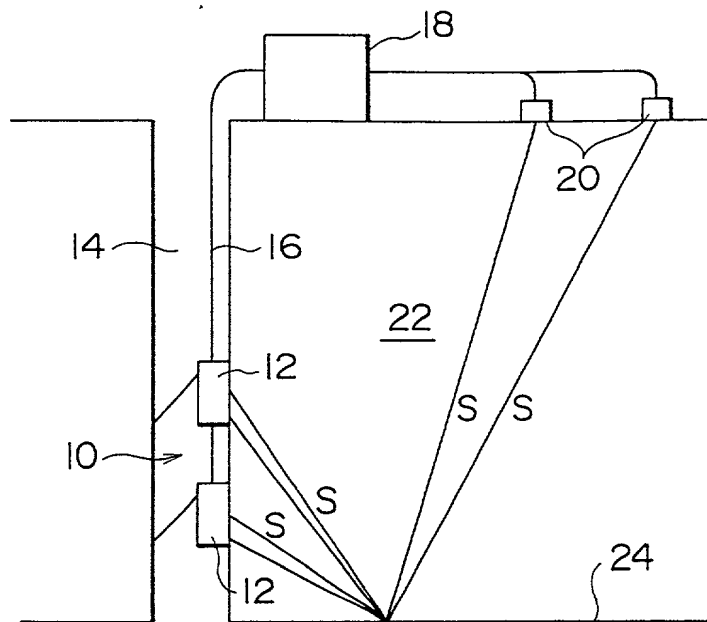
25     13     A method as claimed in claim 1, further comprising validating designated potential source locations by propagating ray traces from the potential source locations back to the receiver locations via the target, and identifying on the target reflection points for the ray traces.

## ABSTRACT

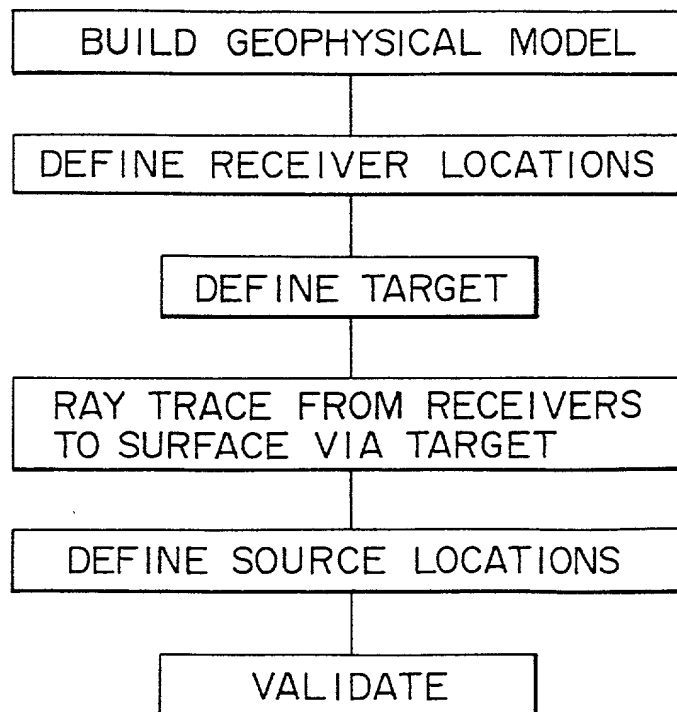
A method for the design of VSP surveys for the purpose of imaging a reef in the formations surrounding the well in question. The basic steps include:

- 5       - building a geophysical model;
- defining receiver locations in the well within the model;
- defining the target (reef);
- ray tracing from receivers to surface via target;
- defining source locations on surface based on ray density pattern; and
- 10     - validate by ray tracing from source locations to receiver locations via target.

# FIG. 1



# FIG. 2





## DECLARATION FOR PATENT APPLICATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name, and

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

## METHOD OF DESIGNING GEOPHYSICAL SURVEYS

the specification of which

☒ is attached hereto.

☐ was filed on \_\_\_\_\_  
as United States Application Number or PCT International Application  
Number \_\_\_\_\_

and was amended on (if applicable) \_\_\_\_\_

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR §1.56.

I hereby claim foreign priority benefits under 35 U.S.C. §119(a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International Application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)		Priority Claimed
_____	/ /	<input type="checkbox"/> YES <input type="checkbox"/> NO
(Number) (Country)	D/M/YR FILED	
_____	/ /	<input type="checkbox"/> YES <input type="checkbox"/> NO
(Number) (Country)	D/M/YR FILED	
_____	/ /	<input type="checkbox"/> YES <input type="checkbox"/> NO
(Number) (Country)	D/M/YR FILED	

I hereby claim the benefit under 35 U.S.C. §119(e) of any United States provisional application(s) listed below:

\_\_\_\_\_  
Application No.

\_\_\_\_\_  
Filing Date



Application No.

Filing Date

I hereby claim the benefit under 35 U.S.C. §120 of any United States application(s), or §365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. §112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

Application Serial No.	Filing Date	Status-patented, pending, abandoned
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Application Serial No.	Filing Date	Status-patented, pending, abandoned
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As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

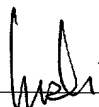
John J. Ryberg, #31,134; Brigitte L. Jeffery, #38,925; Steven L. Christian, #38,106; and Victor H. Segura, #44,329.

I hereby request that all correspondence, notices, official letters and other communication be directed to: Schlumberger Oilfield Services, ATTN: Intellectual Property Counsel, 200 Gillingham Lane MD 200-9, Sugar Land, Texas 77478; and that all telephone calls be directed to: (281) 285-7067.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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